ELSEVIER

Agricultural and Forest Meteorology 70 (1994) 247–258

AGRICULTURAL AND FOREST METEOROLOGY

Cotton evapotranspiration under field conditions with CO_2 enrichment and variable soil moisture regimes

D.J. Hunsaker*[,a], G.R. Hendrey[b], B.A. Kimball[a], K.F. Lewin[b], J.R. Mauney[c], J. Nagy[b]

[a]*USDA, ARS, US Water Conservation Laboratory, 4331 East Broadway Road, Phoenix, AZ 85040, USA*
[b]*Department of Applied Science, Brookhaven National Laboratory, Upton, NY 11973, USA*
[c]*USDA, ARS, Western Cotton Research Laboratory, Phoenix, AZ 85040, USA*

Received 1 September 1992; revision accepted 22 November 1993

Abstract

The CO_2 concentration of the atmosphere is predicted to double by the next century, and this is expected to increase significantly the growth and yield of many important agricultural crops. One consequence of larger and more vigorous plants may be increased crop evapotranspiration (*ET*) and irrigation water requirements. The objective of this work was to determine *ET* of cotton (*Gossypium hirsutum* L. cv. 'Deltapine 77') grown under ambient (about 370 μmol mol^{-1}) and enriched (550 μmol mol^{-1}) CO_2 concentrations for both well-watered and water-stress irrigation managements. Studies were conducted in 1990 and 1991 within a large, drip-irrigated cotton field in central Arizona. Cotton *ET* was measured during the growing seasons using a soil water balance, based on neutron gauge soil water measurements. *ET*, for periods from 7 to 14 days, was not significantly different between ambient and enriched CO_2 treatments at the 0.05 probability level, and the total seasonal *ET* for the CO_2 treatments varied by 2% or less in either year. However, water-stress treatments, which were initiated on 3 July (day of year (DOY) 184) in 1990 and on 20 May (DOY 128) in 1991, had significantly lower ($P < 0.05$) *ET* than well-watered treatments starting at the end of July in 1990 and in early July in 1991 when the plants were about 75–90 days old. The result that CO_2 enrichment to 550 μmol mol^{-1} did not significantly change the *ET* of cotton was consistent with the results of co-investigators who measured *ET* in the same experiments using stem flow gauges and an energy balance. This result implies that irrigation water use would not have to be increased to produce cotton in a future high-CO_2 world. However, if a concomitant change in climate occurs, such as global warming, cotton evapotranspiration may change in response to the changed weather condition.

* Corresponding author.

Elsevier Science B.V.
SSDI 0168-1923(93)05038-T

1. Introduction

The atmosphere's CO_2 concentration is projected to be double the current concentration of about 370 μmol mol^{-1} by the next century (Trenberth, 1991; Allen et al., 1991), and this change is expected to increase significantly the growth and yield of many important agricultural crops (Kimball, 1983). However, one of the possible consequences of larger and more vigorous plants is an increase in crop evapotranspiration (*ET*). Because *ET* influences irrigation water use and management, the effects of increased global CO_2 concentrations on crop *ET* could have a profound impact on irrigated crop production and water resources.

Elevated concentrations of CO_2 affect several mechanisms that influence plant water use, and it is not clear what the resultant changes in *ET* will be. Allen (1991) reviewed the relationships between plant growth, transpiration and elevated CO_2 which have been established in research. Increased CO_2 concentration tends to accelerate the growth and leaf area expansion of plants, which may increase the transpiration of water. However, increased CO_2 also tends to reduce the leaf stomatal conductance of water vapor for most plants, which may decrease transpiration.

Previous experimental studies involving CO_2 enrichment and *ET* have been documented for several agricultural crops, including cotton (Kimball et al., 1983, 1984), soybean (Jones et al., 1985), grain sorghum (Chaudhuri et al., 1986), rice (Baker et al., 1990) and winter wheat (Chaudhuri et al., 1990). Some of the investigators cited above reported differences in *ET* owing to CO_2 enrichment, although in general the differences have been small and inconsistent. For example, Kimball et al. (1983) using lysimeters, found seasonal *ET* changes of -9% and -4% for cotton enriched at CO_2 concentrations of 500 μmol mol^{-1} and 650 μmol mol^{-1}, respectively, in open-top chamber experiments conducted in Arizona. However, in a similar study (Kimball et al., 1984) they found no effect of enriched CO_2 on cotton *ET*. Because these experimental studies were conducted exclusively in enclosures to control CO_2 fumigation of plants, the environment was significantly altered from that under which crops are normally grown in an open field.

Recognizing the need to eliminate the effects imposed by walled chambers in CO_2 enrichment experiments, a free-air CO_2 enrichment (FACE) system was developed to evaluate the effects of increased CO_2 on crop response in a typical agricultural environment (Hendrey and Kimball, 1994). Experiments were conducted in 1990 and 1991 using the FACE system in a large, irrigated cotton field in central Arizona. The objective of this work was to determine *ET*, using the soil water balance method, for cotton grown under ambient (about 370 μmol mol^{-1}) and elevated (550 μmol mol^{-1}) CO_2 concentrations for both well-watered and water-stress irrigation managements. Complementary work by Dugas et al. (1994), using stem flow gauges, and by Kimball et al. (1994), using an energy balance approach, also sought to determine any impact of CO_2 on *ET* in the same FACE experiments.

2. Methods

2.1. Experimental design and crop management

Cotton (*Gossypium hirsutum* L. 'Deltapine 77') was grown in 1990 and 1991 on a field site at the University of Arizona, Maricopa Agricultural Center, located about 40 km south of Phoenix, Arizona. The soil is a Trix clay loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents). Total plant available water in a potential root zone of 1.8 m is about 180 mm. Water content averages $30 \pm 5\%$ and $20 \pm 2\%$, by volume, at soil matric potentials of -33 kPa and -1500 kPa within the top 0.7 m of the soil profile, respectively (Post et al., 1988), and the corresponding values for a soil depth of 0.7–2.0 m are $22 \pm 4\%$ and $12 \pm 3\%$, respectively (F.D. Whisler, personal communication, 1992). The cotton was planted in raised beds in rows, 1.02 m apart, on 23 April (day of year [DOY] 113) in 1990 and 16 April (DOY 106) in 1991. Water was supplied to the crop with a subsurface drip system with a single, micro-tube line per row at 0.18–0.24 m below the soil surface. Emitter outlets were spaced at 0.40 m along the tube line. Irrigation water application quantities were measured with flow meters during the season (Lewin et al., 1994). After planting, approximately 290 mm and 270 mm of water were applied to the entire field for seed germination in 1990 and 1991, respectively. Cotton plant population was established at 10 plants per linear meter of row by thinning and transplanting. Cotton plants were harvested weekly throughout the season until late September in both years (Mauney et al., 1994).

Plot diagrams and a complete description of the FACE exposure and monitoring system have been provided by Lewin et al. (1994) and Nagy et al. (1994). The FACE technique was used to enrich four circular plots, 23 m (1990) and 25 m (1991) in diameter, to a CO_2 concentration of 550 μmol mol^{-1}. These four plots made up the FACE treatment. Plants in the FACE treatment were exposed to daytime elevated CO_2 concentrations, from shortly after crop emergence until mid-September. Four matching circular plots, with no CO_2 enrichment, were also installed in the field. These ambient CO_2 (about 370 μmol mol^{-1}) plots formed the control treatment.

The experimental design was a split plot, laid out as a randomized complete block on the main effect, CO_2, replicated four times. Each of the eight circular plots in the field were split into two semicircular subplots, with each side receiving either a well-watered ('wet') or water-stress ('dry') irrigation treatment.

Irrigation water requirements for the wet treatment were estimated as pan evaporation (in 1990) and as grass-reference crop evapotranspiration (ET_0; in 1991) since the previous irrigation, multiplied by the cotton's leaf area index (LAI) divided by three. Above an LAI of three, water requirements were estimated as pan evaporation (1990) and as ET_0 since the previous irrigation. LAI was determined from weekly plant harvests. Pan evaporation was that from a standard Class A evaporation pan, placed adjacent to one of the FACE treatment plots. The ET_0, calculated from the modified Penman equation (Doorenbos and Pruitt, 1977), was provided in 1990 and 1991 by the University of Arizona, AZMET meteorological station (Brown, 1987), located about 2 km from the field site. In 1990, irrigation frequency was every 7 days, beginning on 20 May (DOY 140). After 3 July 1990 (DOY 184), it was every 3–4 days until 20 September (DOY 263). In 1991, irrigation frequency was every 6–7 days, beginning on 8 May (DOY 128). After 1 July 1991 (DOY 182), it was every 2–3 days until 13 September (DOY 256).

Plots of the dry irrigation treatment were irrigated on the same days as those of the wet treatment in both years. Beginning on 3 July (DOY 184) in 1990 and on 20 May (DOY 140) in 1991, the dry treatments received irrigation amounts equal to 75% and 67% of that given to the wet treatments in 1990 and 1991, respectively.

The total amount of water applied by the drip system during the season (excluding the initial irrigation for plant establishment) averaged 890 mm and 780 mm for the wet and 760 mm and 520 mm for the dry treatments in 1990 and 1991, respectively. Rainfall amounts during the growing season totaled 125 mm and 41 mm in 1990 and 1991, respectively. Additional details on irrigation management, cultural practices, and fertilization performed during the experiments have been provided by Mauney et al. (1994).

2.2. Soil water content measurements

Soil water content was measured in both the wet and dry treatment sections of the four control and FACE plots with neutron scattering equipment, every 7–14 days during 1990 and 1991. In 1990, two neutron access tubes were installed in each wet and dry treatment section to a 2.0 m soil depth in April, just after planting. One of the two tubes was placed in the center of a raised bed and the other was placed 1 m away in the center of an adjacent furrow, 0.5 m from the drip line. Tubes placed in the beds were positioned approximately equidistant between two emitter openings. In 1991, access tubes were again installed to a 2.0 m soil depth in April, just after planting. In three of the four control and FACE plots, the placement and number of access tubes were the same as in 1990. However, in one control and FACE plot, six access tubes were installed 1 m apart in both the wet and dry irrigation treatment sections. Four of these were placed in the center of four adjacent beds and the other two were placed in the center of two furrows located between two adjacent beds. The extra tubes were used primarily to provide additional information on the variability of soil water within plots.

A Campbell Pacific Nuclear neutron moisture gauge (Model 503; Martinez, CA) was used to monitor soil water contents. A calibration curve, developed for the soil, was used to convert the neutron gauge readings to volumetric soil water contents. Soil water content measurements were made from 0.2 to 2.0 m, in 0.2 m increments, beginning on 1 May 1990 (DOY 121) and 23 April 1991 (DOY 106). Measurements continued until 26 September (DOY 269) in 1990 and 17 October (DOY 290) in 1991. In both years, measurements were taken in the morning hours and were generally completed by noon.

2.3. Soil water balance

The soil water balance technique (Jensen et al., 1990) was used to estimate cotton

ET for all treatments. The method requires measurement of soil water depletion over the depth of the effective root zone for a given time interval. Cotton *ET* was calculated over time intervals of 7–14 days beginning on 9 May 1990 (DOY 129) and 2 May 1991 (DOY 122) (about a week after the initial irrigation watering was completed), until the end of September in 1990 and mid-October in 1991. A one-dimensional soil water balance equation was used to calculate cotton *ET* (mm) as follows:

$$ET = \sum_{i=1}^{n} (\theta_1 - \theta_2)\Delta S_i + I + R \qquad (1)$$

where n is the number of depth increments of the effective root zone, ΔS_i is the thickness of each depth increment (in mm), θ_1 and θ_2 are the volumetric soil water contents on the first and second sampling dates at depth i (in m^3 m^{-3}), respectively, I is the depth of irrigation water applied between sampling dates (in mm), and R is the amount of rainfall between sampling dates that does not run off the area (in mm). Dividing the estimated *ET* by the number of days between sampling gives the *ET* rate (mm day^{-1}).

It was necessary to make several assumptions for the calculation of Eq. (1), particularly in consideration of the multi-dimensional drip irrigation infiltration, soil water contents and plant water extraction. First, the maximum depth of the effective cotton root zone was assumed to be 1.8 m (Doorenbos and Kassam, 1979; Bucks et al., 1988). Second, the one-dimensional average depth of irrigation water applied to a plot was assumed to be equal to that which infiltrated within the area bounded by the access tube at the drip line and the access tube 0.5 m from the drip line. Eq. (1) was computed separately for both access tube sites in a plot and the average *ET* of the pair was taken as the estimate within the plot. In 1991, three pairs were computed for the control and FACE plots that had six access tubes. Third, plant extraction of water was assumed to occur uniformly within the area bounded by the access tube pairs. Early in the growing season, plant roots would be expected to be more concentrated below the drip line in the center of the bed. However, differences in soil water depletion rates calculated separately for access tubes in beds and furrows during May and early June in 1991 were less than 5%. Also, root length densities sampled in June in both 1990 and 1991 by Prior et al. (1994) at 0.0 m and 0.5 m from the drip line differed by less than 10%. Finally, with one exception in early 1990, drainage below a cotton root depth of 1.8 m was assumed to be negligible. This assumption was based on evaluation of soil water measurements taken both before and after several irrigations during the season, which indicated little water penetration below a soil depth of 1.2 m. However, possible drainage occurred early in the 1990 season when a large volume of water (approximately 140 mm) was applied to a wet soil profile during a 5 day irrigation between 20 and 25 May (DOY 140 and 145). Consequently, the *ET* rate for each site during the time interval between 17 and 31 May 1990 (DOY 137 and 151) was assumed to be the average of the two *ET* rates calculated for intervals immediately before and after that interval by Eq. (1).

Total seasonal *ET* was calculated as the summation of *ET* over all time intervals during the crop season.

Table 1
Average volumetric soil water content percentage on 9 May 1990 (DOY 129) and 2 May 1991 (DOY 122) for the control–dry (CD), control–wet (CW), FACE–dry (FD), and FACE–wet (FW) treatments (coefficients of variation are given in parentheses)

Year	Treatment	Soil depth	
		0–0.7 m	0.7–1.8 m
1990	CD	24.4(0.13)	20.9(0.20)
	CW	24.0(0.12)	21.6(0.10)
	FD	27.1(0.04)	18.7(0.36)
	FW	25.3(0.04)	18.5(0.29)
1991	CD	25.9(0.09)	19.8(0.10)
	CW	25.0(0.10)	19.2(0.14)
	FD	26.0(0.03)	17.4(0.31)
	FW	25.1(0.06)	17.3(0.36)

2.4. 'Background' cotton evapotranspiration

For comparison purposes, cotton *ET* for the field as a whole (the well-watered, ambient CO_2 condition) was also estimated using the ET_0, described above, multiplied by a crop coefficient (k_c) for cotton. This estimate ($k_c \times ET_0$) was calculated for the 7–14 day intervals used for the soil water balance *ET* (Eq. (1)) over the growing season in each year. The cotton k_c values used were from Pruitt et al. (1987).

2.5. Data analysis

Analysis of variance (ANOVA) and related statistical procedures were performed on the SAS PC system (Statistical Analysis Systems Institute Inc., 1988). A two-factor ANOVA model was used in the data analysis. The model had two parts: Part (1) included the block effect (ρ), the CO_2 main effect (α) and the error term ($\rho\alpha$); Part (2) included the irrigation subplot effect (β), the interaction term ($\alpha\beta$) and the error term ($\rho\alpha\beta$). The least significant difference (LSD) criterion was used for comparison of treatment means (Snedecor and Cochran, 1967).

3. Results

3.1. Soil water depletion

The 1.8 m soil profile was assumed to be near field capacity on 9 May 1990 (DOY 129) and 2 May 1991 (DOY 122), 6 days and 7 days after 290 mm and 270 mm of water had been applied for crop establishment, respectively. Average volumetric water contents for treatments on the above dates (Table 1) were between 24 and 27% within the 0–0.7 m soil profile and between 17 and 22% within a soil depth of 0.7–1.8 m. The coefficients of variation (CV values) among replicates within treat-

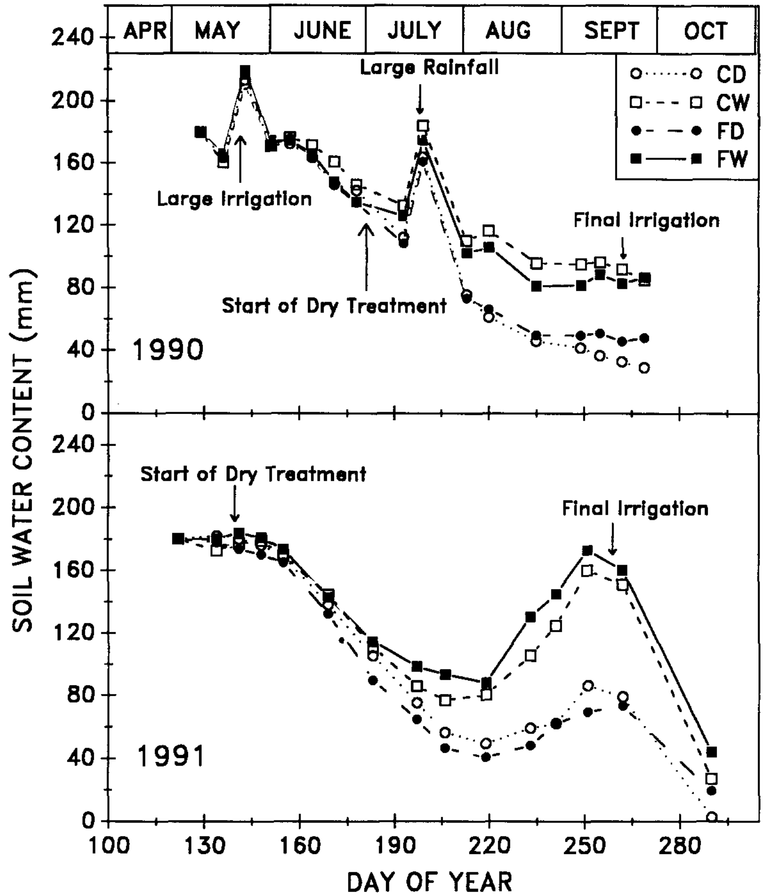

Fig. 1. Distribution of plant-available soil water content within a 1.8 m soil profile for the control–dry (CD), control–wet (CW), FACE–dry (FD) and FACE–wet (FW) treatments in 1990 and 1991. Each data point is the average of four replicates.

ments (Table 1) indicated that the water contents were more variable within the lower soil depth (CV values of 0.10–0.36) than at the surface 0–0.7 m (CV values of 0.03–0.12).

In 1990, the 1.8 m soil profile (Fig. 1) gained water (exceeded field capacity) in late May, during a large irrigation (140 mm) given between 20 and 25 May (DOY 140 and 145). Much of the water added to the profile from the irrigation presumably drained below 1.8 m by 1 June 1990 (DOY 152). Thereafter, soil water content decreased in all treatments during June and early July 1990, and then increased after a large rainfall of 62 mm on 14 July (DOY 195). Soil water content decreased rapidly in all treatments between late July and August 1990, indicating that the wet treatment was not receiving enough water during this period. In 1991, soil water content (Fig. 1) decreased rapidly in all treatments until 25 July (DOY 206). Because it was felt that the wet treatments were not receiving enough water, irrigation frequency and volume were

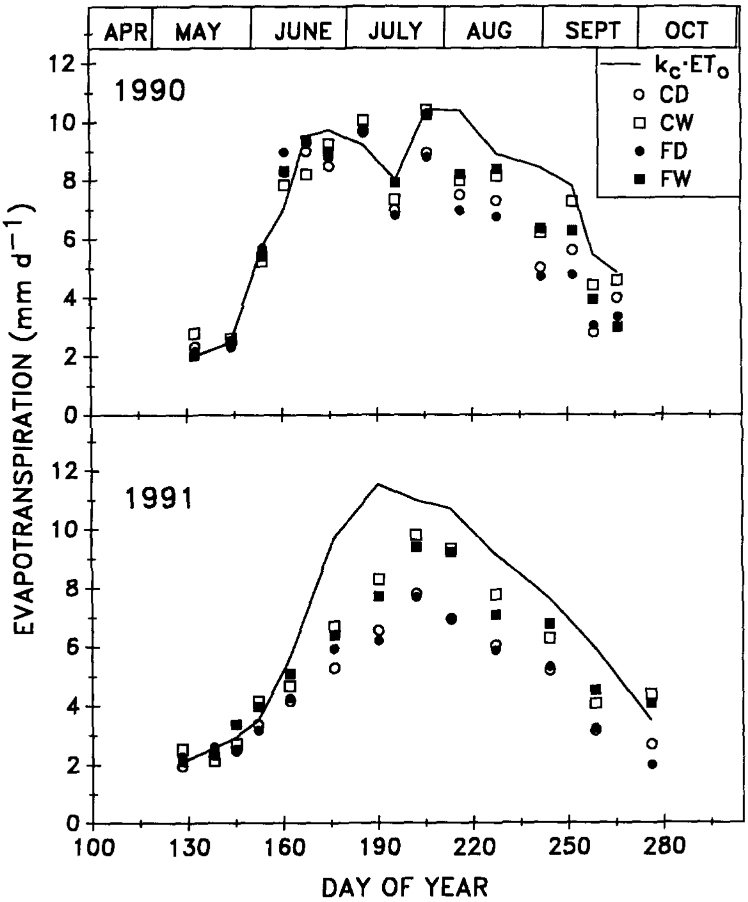

Fig. 2. Comparison of evapotranspiration (ET) between the control–dry (CD), control–wet (CW), FACE–dry (FD) and FACE–wet (FW) treatments and $k_c \times ET_0$ in 1990 and 1991. Each data point is the average of four replicates.

adjusted to provide about 15% more water to all treatments, starting in late July 1991. This adjustment increased the soil water content in all treatments by mid-August 1991.

Soil water depletion was significantly greater in the dry than in the wet treatments ($P < 0.05$) starting on 1 August 1990 (DOY 213) and 16 July 1991 (DOY 197). However, differences in soil water depletion between control and FACE treatments during either 1990 or 1991 were not significant at $P < 0.05$.

3.2. Evapotranspiration

The 1990 ET rates (Fig. 2) were significantly different ($P < 0.05$) between wet and dry treatments beginning in late July (DOY 206), about 3 weeks after the dry irrigation treatment was imposed, until mid-September. However, analysis of variance

Table 2
Seasonal evapotranspiration (ET) by the soil water balance for the control–dry (CD), control–wet (CW), FACE–dry (FD), and FACE–wet (FW) treatment in 1990 and 1991

Year	Treatment	Evapotranspiration (mm)
1990	CD	901[b]
	CW	993[a]
	FD	887[b]
	FW	982[a]
1991	CD	754[b]
	CW	971[a]
	FD	742[b]
	FW	953[a]

ET values are the means of four replicates.
[ab] Treatment means followed by different letters in a year are significantly different at the 0.05 level using the least significant difference criterion.

failed to detect significant differences ($P < 0.05$) between control and FACE treatments for any estimate during the season. The CV values for *ET* rate, calculated from the four replicates of each treatment, averaged over the 1990 season were 0.14, 0.11, 0.12 and 0.12 for the control–dry (CD), control–wet (CW), FACE–dry (FW) and FACE–wet (FW), respectively. Soil water balance *ET* for the wet treatment agreed with $k_c \times ET_0$ over much of the 1990 season, although the soil water balance *ET* was 1–3 mm day^{-1} lower than $k_c \times ET_0$ during August and early September. The lower *ET* rates from the water balance may have been caused by crop water stress, as soil water content was observed to be declining in the wet treatments during this period (Fig. 1).

In 1991, significant differences ($P < 0.05$) between wet and dry treatments *ET* rates (Fig. 2) were indicated from early July (DOY 190), about 7 weeks after the dry irrigation treatment was imposed, until the end of the season. As in 1990, analysis of variance failed to detect any effect of CO_2 treatment on *ET* rate in 1991. The seasonal average CV values for *ET* rate were 0.14, 0.10, 0.13 and 0.12 for the CD, CW, FD and FW treatments in 1991, respectively. Soil water balance *ET* values for the wet treatments were considerably lower (about 3–4 mm day^{-1}) than $k_c \times ET_0$ during mid-June to early July in 1991, which indicated that the well-watered plots may have been short of water. Pinter et al. (1994) detected that plant water stress was developing in the wet treatment after 19 June 1991 (DOY 170), from measurements of radiation absorbed by the canopy. After increasing the frequency and amount of irrigations, wet treatment *ET* rates were close to $k_c \times ET_0$ by late July, but remained slightly lower through the end of the season. Comparisons of *ET* measured by the water balance with *ET* measured in the same FACE experiments by an energy balance and sap flow gauges have been presented by Kimball et al. (1994) and Dugas et al. (1994), respectively. In general, *ET* rates from those studies were consistent with the water balance *ET* rate.

The seasonal *ET*, by the water balance (Table 2), was 901 mm, 993 mm, 887 mm and 982 mm for the CD, CW, FD and FW treatments in 1990, respectively, and

754 mm, 971 mm, 742 mm and 953 mm for the CD, CW, FD and FW treatments in 1991, respectively. (For comparison, the average historical seasonal *ET* for fully irrigated cotton in central Arizona from 1 April to 15 November (DOY 091–319) is 1045 mm (Erie et al., 1982)). The large difference in seasonal *ET* for the dry treatments between years (about 150 mm) was expected, as the water deficit was larger and imposed 44 days earlier in the 1991 season than in 1990. Changes in seasonal *ET* owing to CO_2 enrichment were less than −2% over both years and were not significant (Table 2). However, changes in seasonal *ET* caused by reduced irrigation, which were −9% in 1990 and −22% in 1991, were significant at $P < 0.05$. The total biomass of cotton increased by an average of 39% and 22% under CO_2 enrichment for the wet and dry irrigation treatments, respectively (Mauney et al., 1994). Thus, with no significant differences in *ET*, water use efficiency increased proportionately with the increase in cotton growth caused by elevated CO_2.

4. Conclusions

Evapotranspiration, estimated by the soil water balance method, was evaluated for cotton grown in the field under ambient (about 370 μmol mol^{-1}) and enriched (550 μmol mol^{-1}) CO_2 concentrations in the 1990 and 1991 FACE experiments in Arizona. Well-watered and water-stress irrigation treatments were imposed in both years.

It was concluded from this study that cotton *ET* rates, determined for 7–14 day periods over the season, were not significantly different under the two CO_2 concentrations in either year. Neither was there a significant change in seasonal *ET*, which differed by less than 2% between CO_2 concentrations in both cotton seasons. Statistically significant differences in *ET* were found in the water-stress plots under both ambient and enriched CO_2 concentrations. The results of co-investigators, who used a residual energy balance approach and sap flow gauges to measure *ET* in the same FACE experiments, support the conclusion there was no effect of CO_2 on evapotranspiration. Our *ET* results, obtained under conditions typical of agricultural field environments, were also consistent with past studies performed in open-top chambers, which showed that the effects of CO_2 on cotton *ET* are small.

The conclusion from this study implies that water use efficiency increased proportionately with the increase in cotton growth caused by elevated CO_2. It also implies that irrigation water use will not have to be increased to produce cotton in a future high-CO_2 environment. However, if a concomitant change in climate occurs, such as global warming, *ET* may increase in response to the changed weather condition.

Acknowledgments

Special thanks are given to W.L. Alexander and C.K. Arterberry, Agronomist and

Irrigation Technician, USDA–ARS, respectively, for their help in field installations and measurements.

Trade and company names are included for the benefit of the reader, and do not imply any endorsement of the products by the US Department of Agriculture or organizations with which the authors are affiliated.

References

Allen, Jr, L.H., 1991. Effects of increasing carbon dioxide levels and climate change on plant growth, evapotranspiration, and water resources. In: Managing Water Resources in the West under Conditions of Climate Uncertainty. National Academy Press, Washington, DC, pp. 101–147.

Allen, R.G., Gichuki, F.N. and Rosenzweig, C., 1991. CO_2-Induced climatic changes and irrigation-water requirements. J. Water Res. Plann. Manage., ASCE, 117(2): 157–178.

Baker, J.T., Allen, Jr, L.H., Boote, K.J., Jones, P. and Jones, J.W., 1990. Rice photosynthesis and evapotranspiration in subambient, ambient, and superambient carbon dioxide concentrations. Agron. J., 82: 834–840.

Brown, P.W., 1987. User's Guide to the Arizona Meteorological Network. City of Phoenix, Water Conservation and Resource Div. and Arizona Cooperative Extension, Phoenix, AZ, 44 pp.

Bucks, D.A., Allen, S.G., Roth, R.L. and Gardner, B.R., 1988. Short staple cotton under micro and level-basin irrigation methods. Irrig. Sci., 9(3): 161–176.

Chaudhuri, U.N., Burnett, R.B., Kirkham, M.B. and Kanemasu, E.T., 1986. Effect of carbon dioxide on sorghum yield, root growth and water use. Agric. For. Meteorol., 37: 109–122.

Chaudhuri, U.N., Kirkham, M.B. and Kanemasu, E.T., 1990. Carbon dioxide and water level effects on yield and water use of winter wheat. Agron. J., 82: 637–641.

Doorenbos, J. and Kassam, A.H., 1979. Yield response to water. Irrigation and Drainage Paper 33. FAO, Rome, 193 pp.

Doorenbos, J. and Pruitt, W.O., 1977. Crop water requirements. Irrigation and Drainage Paper 24. FAO, Rome, 144 pp.

Dugas, W.A., Heuer, M.L., Hunsaker, D., Kimball, B.A., Lewin, K.F., Nagy, J. and Johnson, M., 1994. Sap flow measurements of transpiration from cotton grown under ambient and enriched CO_2 concentrations. Agric. For. Meteorol., 70: 231–245.

Erie, L.J., French, O.F., Bucks, D.A. and Harris, K., 1982. Consumptive use of water by major crops in the Southwestern United States. US Dep. Agric. Conserv. Res. Rep., 29, 40 pp.

Hendrey, G.R. and Kimball, B.A., 1994. The FACE program. Agric. For. Meteorol., 70: 3–14.

Jensen, M.E., Burman, R.D. and Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice, No. 70. American Society of Civil Engineers, New York, 332 pp.

Jones, P., Jones, J.W. and Allen, Jr, L.H., 1985. Seasonal carbon and water balances of soybeans grown under stress treatments in sunlit chambers. Trans. ASAE, 28: 2021–2028.

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Agron. J., 75: 779–788.

Kimball, B.A., Mauney, J.R., Guinn, G., Nakayama, F.S., Pinter, Jr, P.J., Clawson, K.L., Reginato, R.J. and Idso, S.B., 1983. Effects of increasing atmospheric CO_2 on the yield and water use of crops. Series: Response of Vegetation to Carbon Dioxide, No. 021. US Department of Energy, Carbon Dioxide Research Division, and US Department of Agriculture, Agricultural Research Service, Washington, DC, 37 pp.

Kimball, B.A., Mauney, J.R., Guinn, G., Nakayama, F.S., Pinter, Jr, P.J., Clawson, K.L., Idso, S.B., Butler, Jr, G.D. and Radin, J.W., 1984. Effects of increasing atmospheric CO_2 on the yield and water use of crops. Series: Response of Vegetation to Carbon Dioxide, No. 023. US Department of Energy, Carbon Dioxide Research Division, and US Department of Agriculture, Agricultural Research Service, Washington, DC, 60 pp.

Kimball, B.A., LaMorte, R.L., Seay, R.S., Pinter, Jr, P.J., Rokey, R.R., Hunsaker, D.J., Dugas, W.A., Heuer, M.L., Mauney, J.R., Hendrey, G.R., Lewin, K.F. and Nagy, J., 1994. Effects of free-air CO_2 enrichment on energy balance and evapotranspiration of cotton. Agric. For. Meteorol., 70: 259–278.

Lewin, K.F., Hendrey, G.R., Nagy, J. and LaMorte, R.L., 1994. Design and application of a free-air carbon dioxide enrichment facility. Agric. For. Meteorol., 70: 15–29.

Mauney, J.R., Kimball, B.A., Pinter, Jr, P.J., LaMorte, R.L., Lewin, K.F., Nagy, J. and Hendrey, G.R., 1994. Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. Agric. For. Meteorol., 70: 49–67.

Nagy, J., Lewin, K.F., Hendrey, G.R., Hassinger, E. and LaMorte, R., 1994. FACE facility CO_2 concentration control and CO_2 use in 1990 and 1991. Agric. For. Meteorol., 70: 31–48.

Pinter, Jr, P.J., Kimball, B.A., Mauney, J.R., Hendrey, G.R., Lewin, K.F. and Nagy, J., 1994. Effects of free-air carbon dioxide enrichment on PAR absorption and conversion efficiency by cotton. Agric. For. Meteorol., 70: 209–230.

Post, D.F., Mack, C., Camp, P.D. and Suliman, A.S., 1988. Mapping and characterization of the soils on the University of Arizona, Maricopa Agricultural Center. Proceedings of Hydrology and Water Resources in Arizona and the Southwest, Arizona–Nevada Academy of Science, University of Arizona Press, Tucson, AZ, 18: 49–60.

Prior, S.A., Rogers, H.H., Runion, G.B. and Mauney, J.R., 1994. Effects of free-air CO_2 enrichment on cotton root growth. Agric. For. Meteorol., 70: 69–86.

Pruitt, W.O., Fereres, E., Kaita, K. and Synder, R.L., 1987. Reference evapotranspiration (ET_0) for California. Agric. Exp. Sta. Bull. 1922. University of California, Davis, California, 16 pp.

Snedecor, G.W. and Cochran, W.G., 1967. Statistical Methods. Iowa State University Press, Ames, 563 pp.

Statistical Analysis Systems Institute Inc., 1988. SAS/STAT User's guide. Release 6.03 edition. SAS Institute Inc., Cary, NC, 1028 pp.

Trenberth, K.E., 1991. Climate change and climate variability: the climate record. In: Managing Water Resources in the West under Conditions of Climate Uncertainty. National Academy Press, Washington, DC, pp. 47–70.